# Electronic Devices and Circuit Theory

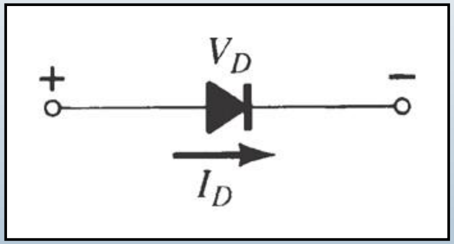
Boylestad

## Semiconductor Diodes

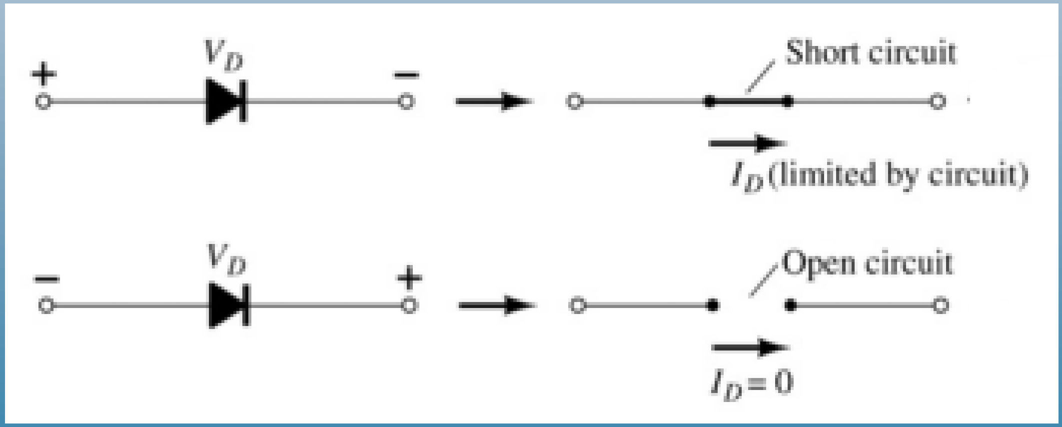
### Chapter 1

# Diodes

**The diode is a 2-terminal device.**

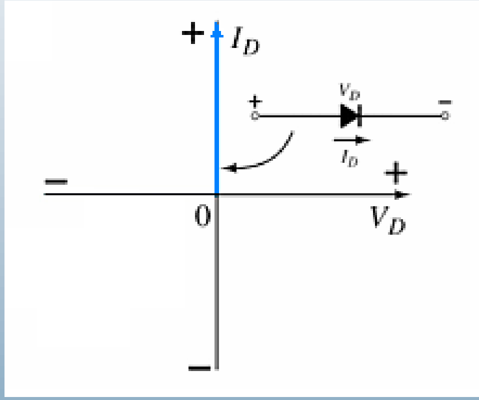



**A diode ideally conducts in only one direction.**



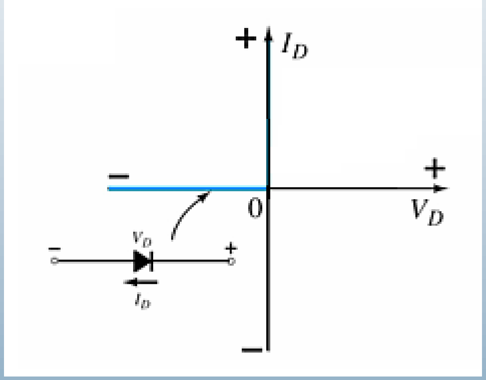
# Diode Characteristics

## Conduction Region




The voltage across the diode is 0 V
The current is infinite
The forward resistance is defined as
$R_F = V_F / I_F$
The diode acts like a short

## Non-Conduction Region




All of the voltage is across the diode
The current is 0 A
The reverse resistance is defined as
$R_R = V_R / I_R$
The diode acts like open

# Semiconductor Materials

**Materials commonly used in the development of semiconductor devices:**

- **Silicon (Si)**
- **Germanium (Ge)**
- **Gallium Arsenide (GaAs)**

# Doping

**The electrical characteristics of silicon and germanium are improved by adding materials in a process called *doping*.**

**There are just two types of doped semiconductor materials:**

## *n*-type

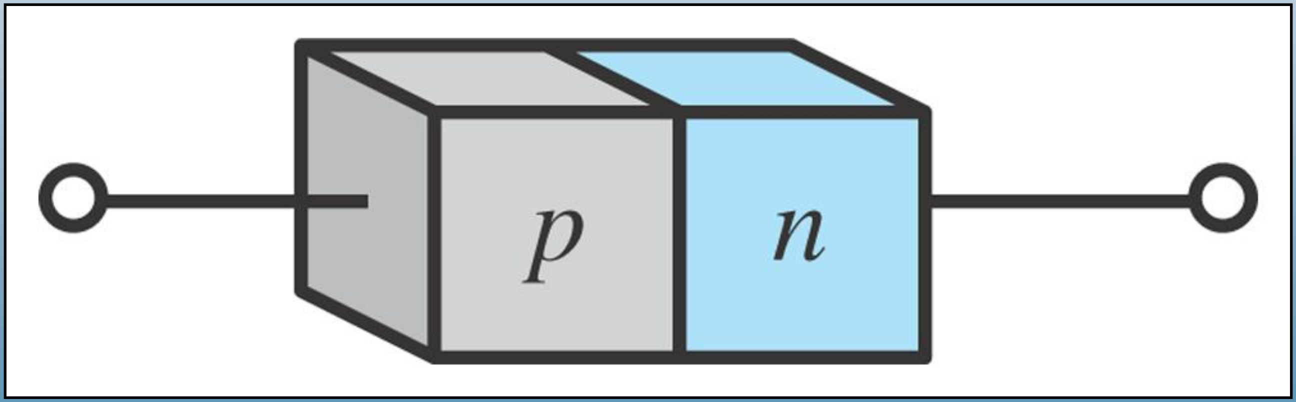
***n*-type** materials contain an excess of conduction band electrons.

## *p*-type

***p*-type** materials contain an excess of valence band holes.

# *p-n* Junctions

**One end of a silicon or germanium crystal can be doped as a *p*-type material and the other end as an *n*-type material.**

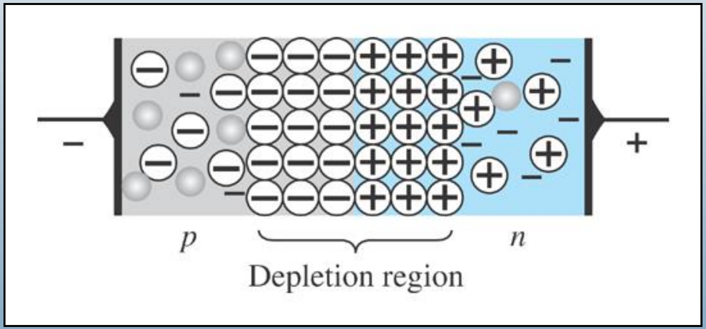



The result is a ***p-n* junction**

# *p-n* Junctions

**At the *p-n* junction, the excess conduction-band electrons on the *n*-type side are attracted to the valence-band holes on the *p*-type side.**

The electrons in the *n*-type material migrate across the junction to the *p*-type material (electron flow).




Electron migration results in a negative charge on the *p*-type side of the junction and a positive charge on the *n*-type side of the junction.

**The result is the formation of a depletion region around the junction.**

# Diode Operating Conditions

**A diode has three operating conditions:**

- **No bias**
- **Reverse bias**
- **Forward bias**

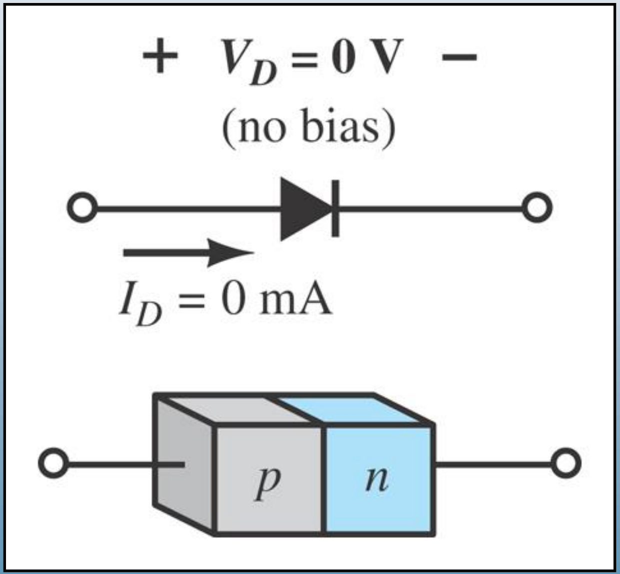
# Diode Operating Conditions

## No Bias

No external voltage is applied: $V_D = 0$ V

There is no diode current: $I_D = 0$ A

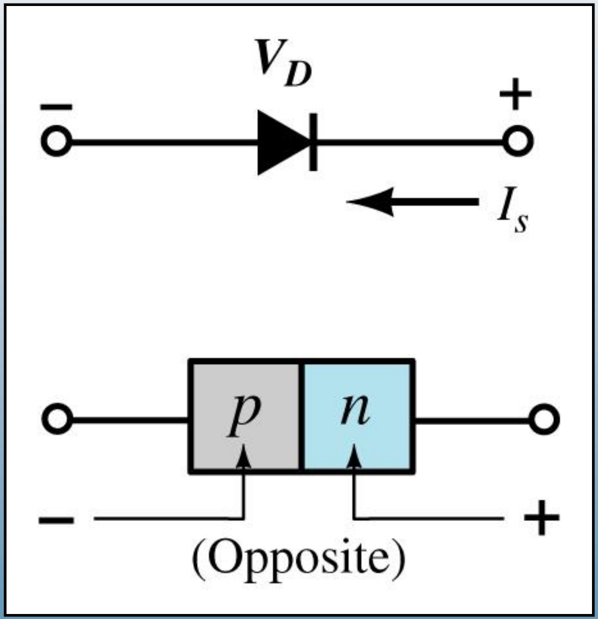
Only a modest depletion region exists



# Diode Operating Conditions

## Reverse Bias

External voltage is applied across the *p-n* junction in the opposite polarity of the *p-* and *n*-type materials.

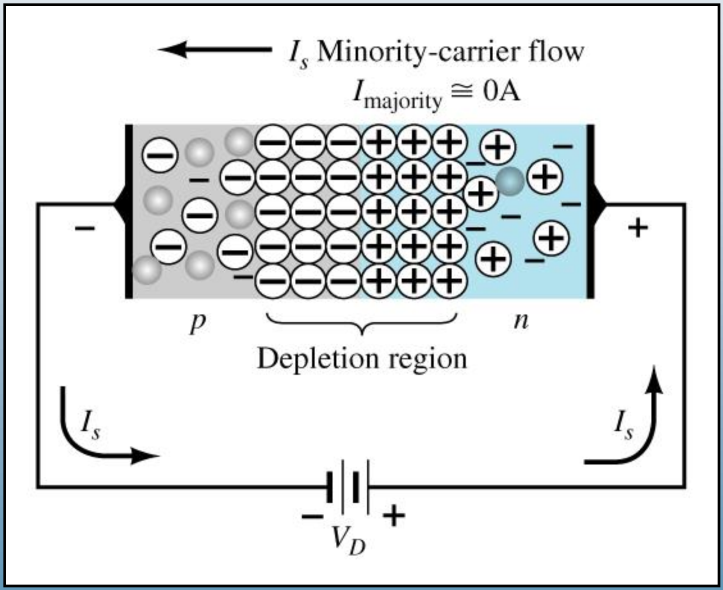


# Diode Operating Conditions

## Reverse Bias

The reverse voltage causes the depletion region to widen.

The electrons in the *n*-type material are attracted toward the positive terminal of the voltage source.

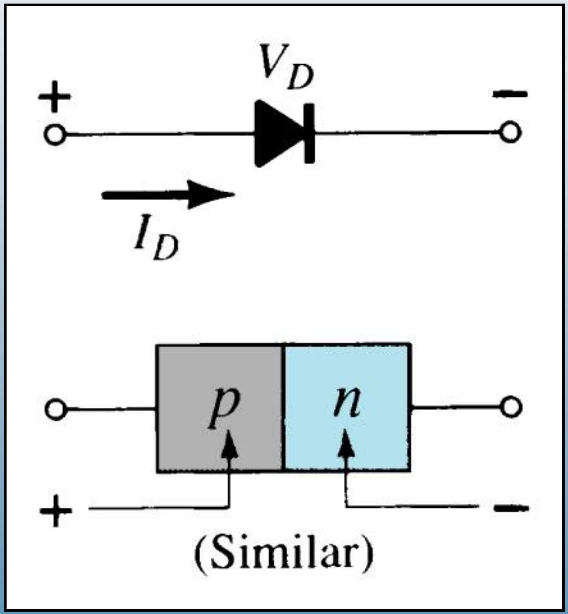



The holes in the *p*-type material are attracted toward the negative terminal of the voltage source.

# Diode Operating Conditions

## Forward Bias

External voltage is applied across the *p-n* junction in the same polarity as the *p-* and *n-* type materials.

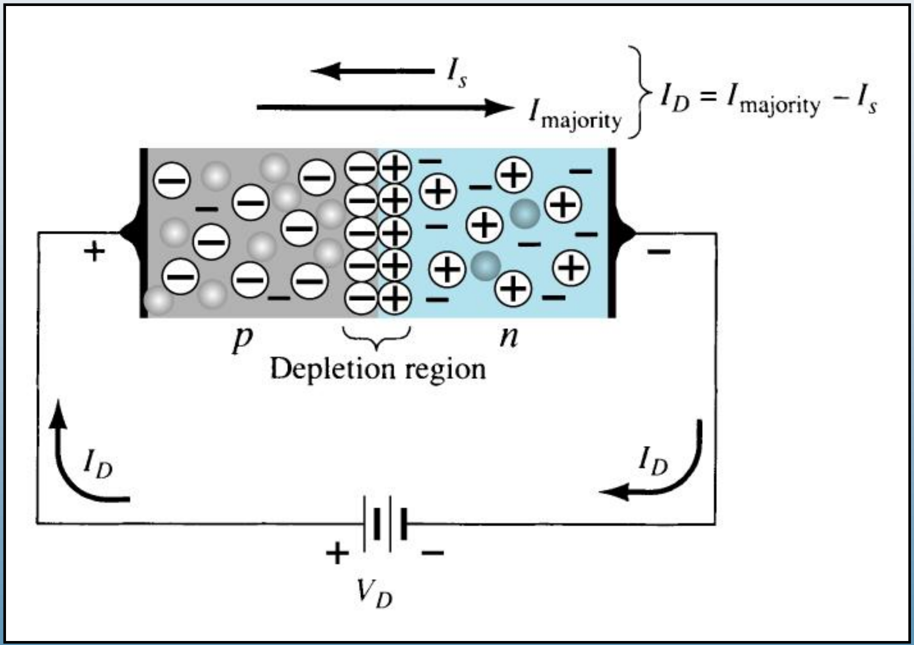


# Diode Operating Conditions

## Forward Bias

The forward voltage causes the depletion region to narrow.

The electrons and holes are pushed toward the *p-n* junction.

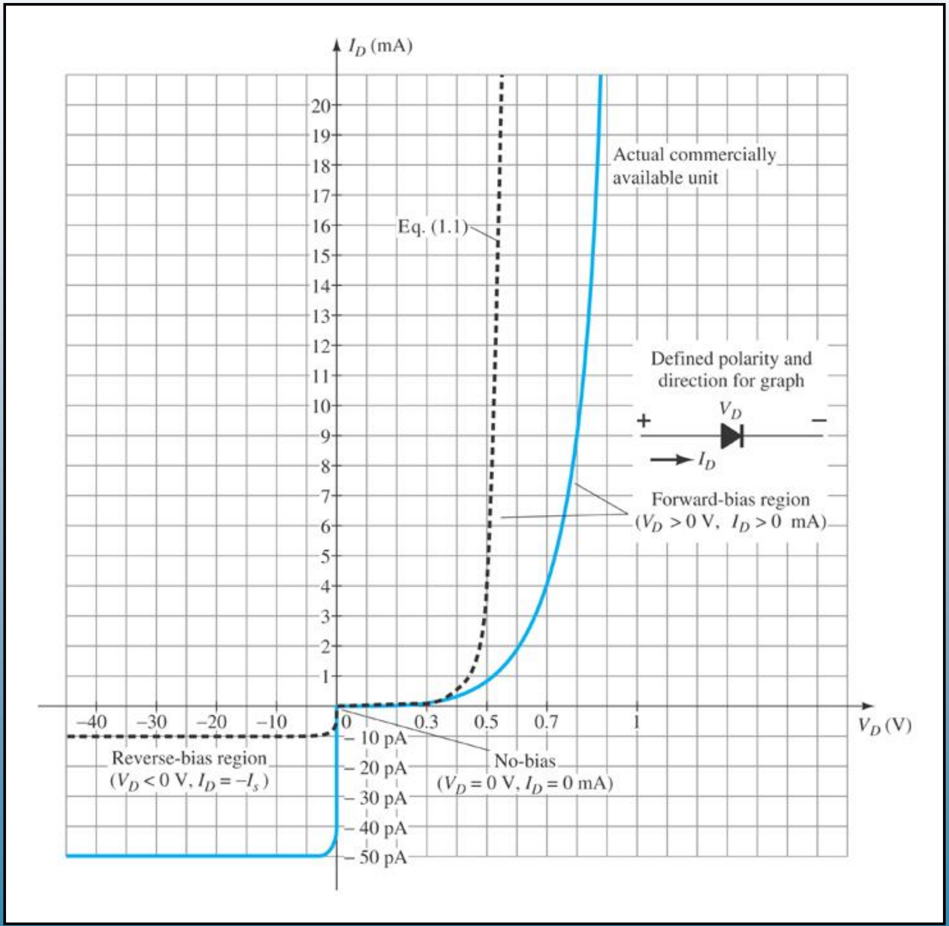



The electrons and holes have sufficient energy to cross the *p-n* junction.

# Actual Diode Characteristics

**Note the regions for no bias, reverse bias, and forward bias conditions.**

Carefully note the scale for each of these conditions.



# Majority and Minority Carriers

*Two currents through a diode:*

## Majority Carriers

The majority carriers in ***n*-type** materials are electrons.

The majority carriers in ***p*-type** materials are holes.

## Minority Carriers

The minority carriers in ***n*-type** materials are holes.

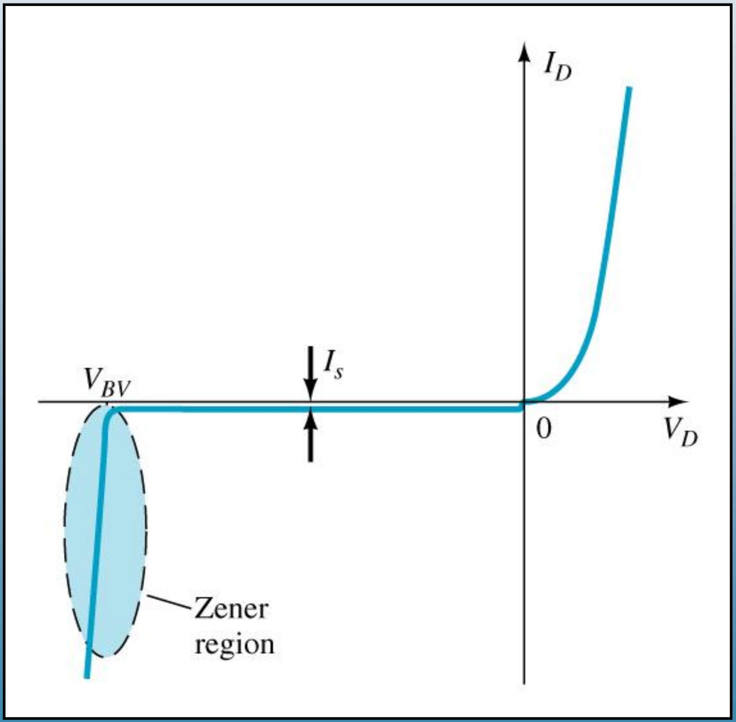
The minority carriers in ***p*-type** materials are electrons.

# Zener Region

## The Zener region is in the diode's reverse-bias region.

At some point the reverse bias voltage is so large the diode breaks down and the reverse current increases dramatically.
The maximum reverse voltage that won't take a diode into the zener region is called the **peak inverse voltage** or **peak reverse voltage.**

The voltage that causes a diode to enter the zener region of operation is called the **zener voltage ($V_Z$)**.



# Forward Bias Voltage

The point at which the diode changes from no-bias condition to forward-bias condition occurs when the electrons and holes are given sufficient energy to cross the p-n junction. This energy comes from the external voltage applied across the diode.

The forward bias voltage required for a:

**gallium arsenide diode ≅ 1.2 V**

**silicon diode ≅ 0.7 V**

**germanium diode ≅ 0.3 V**

# Temperature Effects

**As temperature increases it adds energy to the diode.**

It reduces the required forward bias voltage for forward-bias conduction.

It increases the amount of reverse current in the reverse-bias condition.

It increases maximum reverse bias avalanche voltage.

***Germanium diodes are more sensitive to temperature variations than silicon or gallium arsenide diodes.***

# Resistance Levels

**Semiconductors react differently to DC and AC currents.**

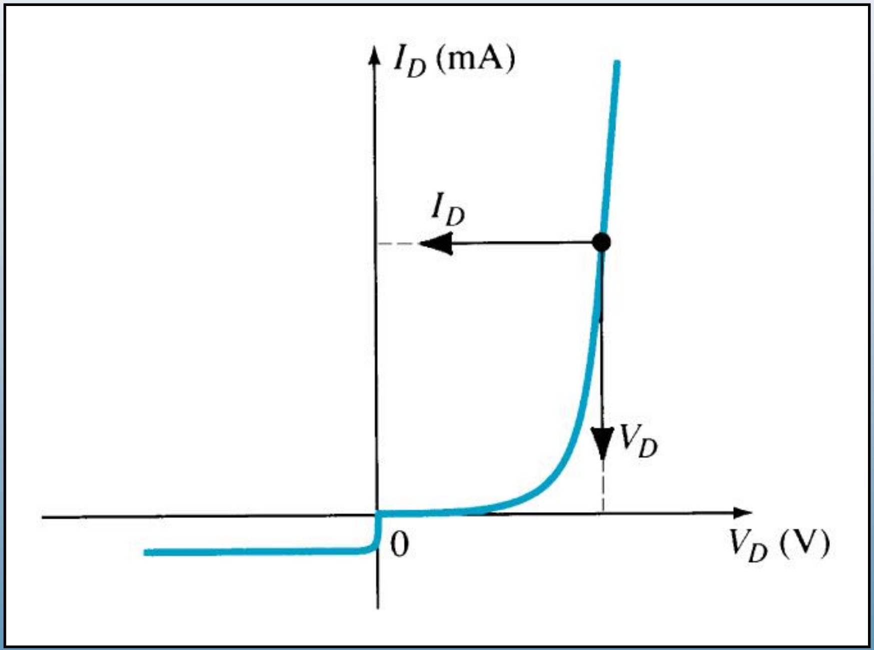
*There are three types of resistance:*

- **DC (static) resistance**
- **AC (dynamic) resistance**
- **Average AC resistance**

# DC (Static) Resistance

For a specific applied DC voltage ($V_D$) the diode has a specific current ($I_D$) and a specific resistance ($R_D$).

$$R_D = \frac{V_D}{I_D}$$



# AC (Dynamic) Resistance

In the forward bias region:

$$r'_d = \frac{26\,mV}{I_D} + r_B$$

The resistance depends on the amount of current ($I_D$) in the diode.

The voltage across the diode is fairly constant (26 mV for 25°C).

$r_B$ ranges from a typical 0.1 Ω for high power devices to 2 Ω for low power, general purpose diodes. In some cases $r_B$ can be ignored.

In the reverse bias region:

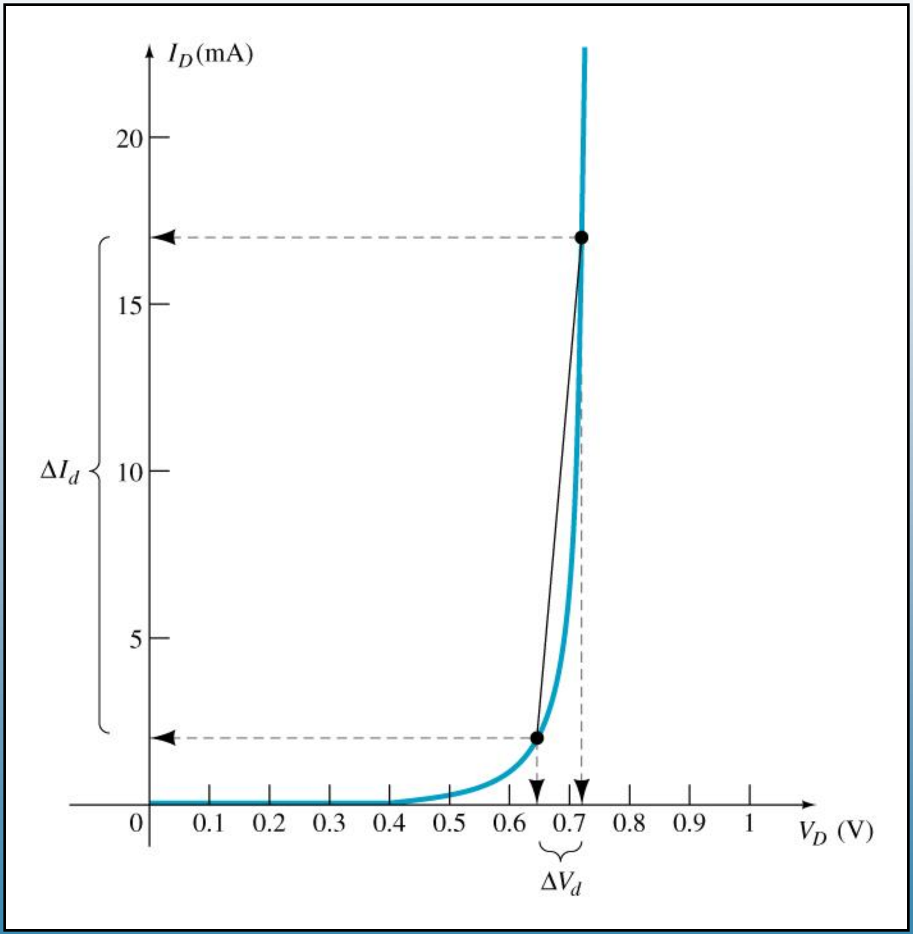
$$r'_d = \infty$$

***The resistance is effectively infinite. The diode acts like an open.***

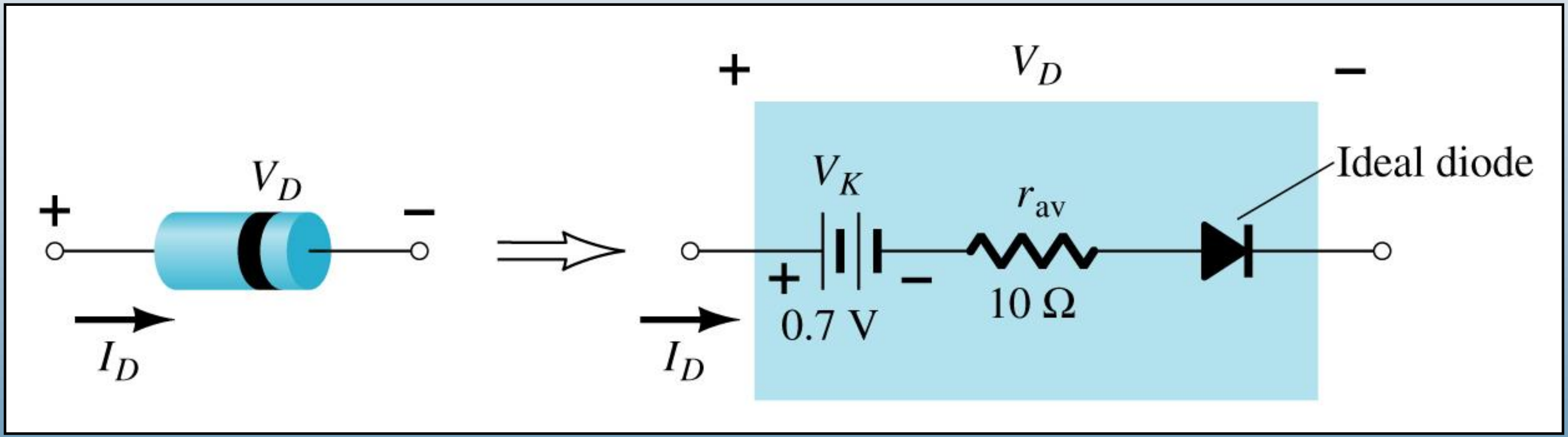
# Average AC Resistance

$$r_{av} = \frac{\Delta V_d}{\Delta I_d} \bigg| \, pt.\, to\, pt.$$

AC resistance can be calculated using the current and voltage values for two points on the diode characteristic curve.



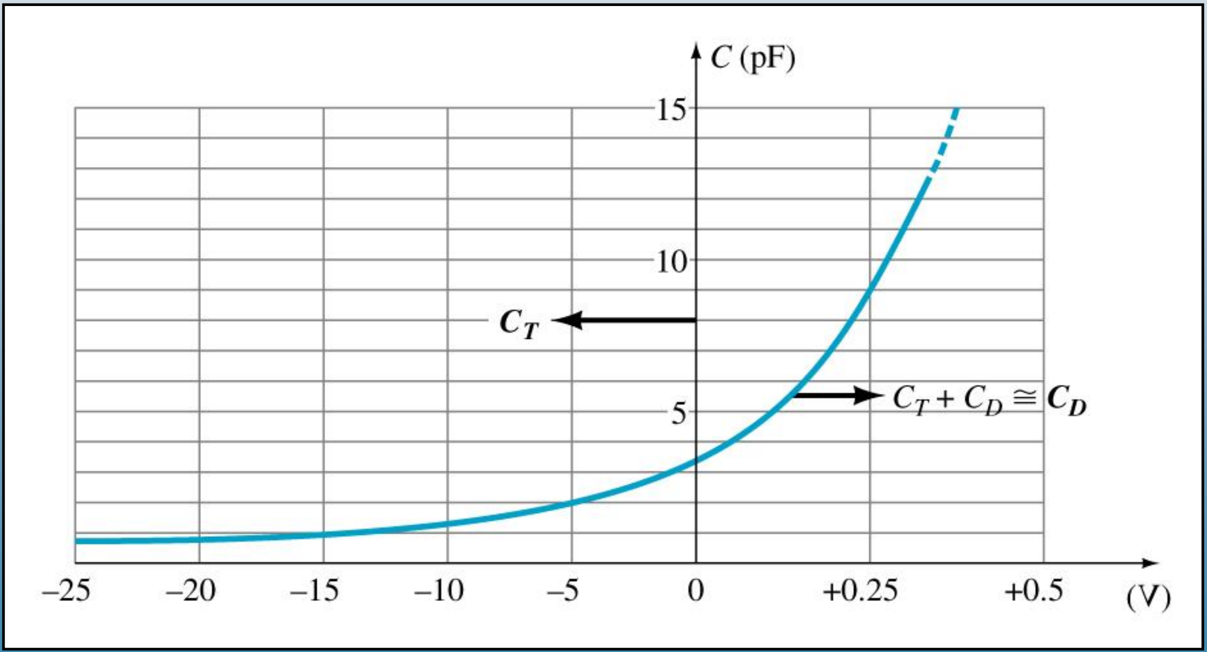
# Diode Equivalent Circuit



# Diode Capacitance

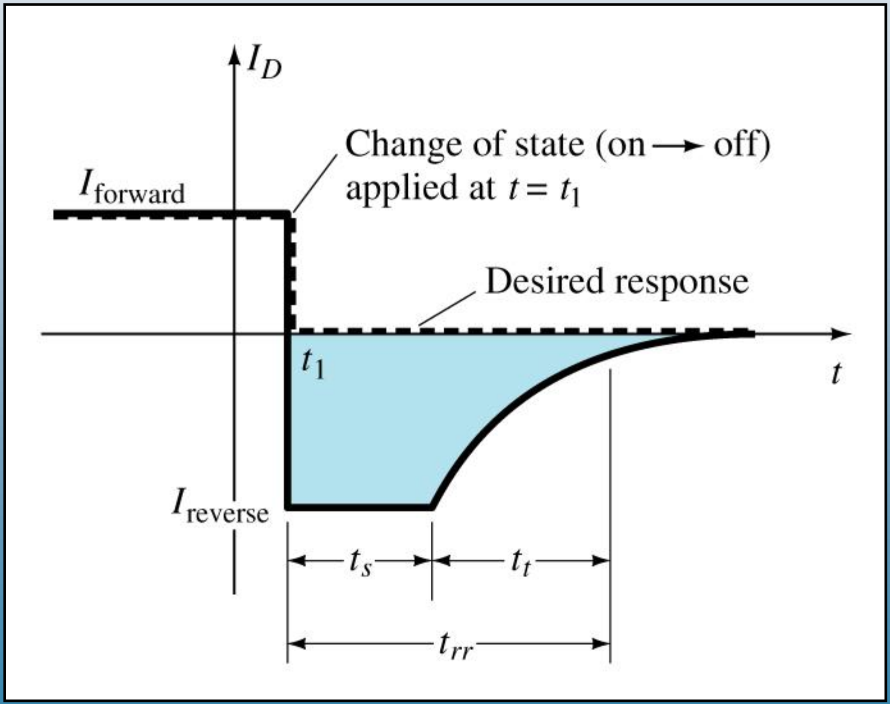
When ***reverse biased***, the depletion layer is very large. The diode's strong positive and negative polarities create capacitance ($C_T$). The amount of capacitance depends on the reverse voltage applied.

When ***forward biased***, storage capacitance or diffusion capacitance ($C_D$) exists as the diode voltage increases.



# Reverse Recovery Time ($t_{rr}$)

***Reverse recovery time** is the time required for a diode to stop conducting when switched from forward bias to reverse bias.*

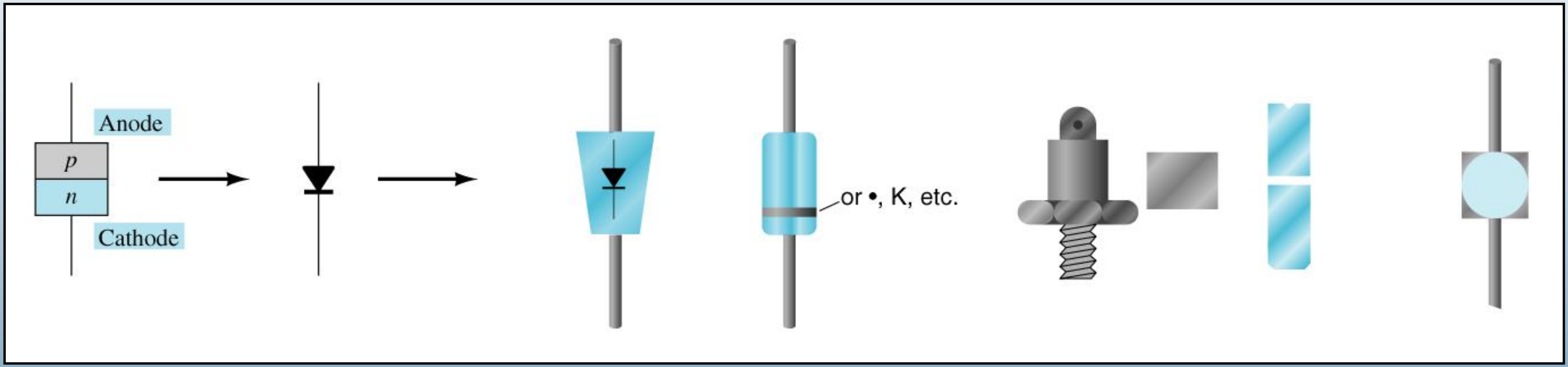


# Diode Specification Sheets

***Diode data sheets contain standard information, making cross-matching of diodes for replacement or design easier.***

1. Forward Voltage ($V_F$) at a specified current and temperature
2. Maximum forward current ($I_F$) at a specified temperature
3. Reverse saturation current ($I_R$) at a specified voltage and temperature
4. Reverse voltage rating, PIV or PRV or $V_{(BR)}$, at a specified temperature
5. Maximum power dissipation at a specified temperature
6. Capacitance levels
7. Reverse recovery time, $t_{rr}$
8. Operating temperature range

# Diode Symbol and Packaging




**The anode is abbreviated A**

**The cathode is abbreviated K**

# Diode Testing

Diodes are commonly tested using one of these types of equipment:

**Diode checker**

**Ohmmeter**

**Curve tracer**

# Diode Checker

Many digital multimeters have a diode checking function.
The diode should be tested out of circuit.

*A normal diode exhibits its forward voltage:*

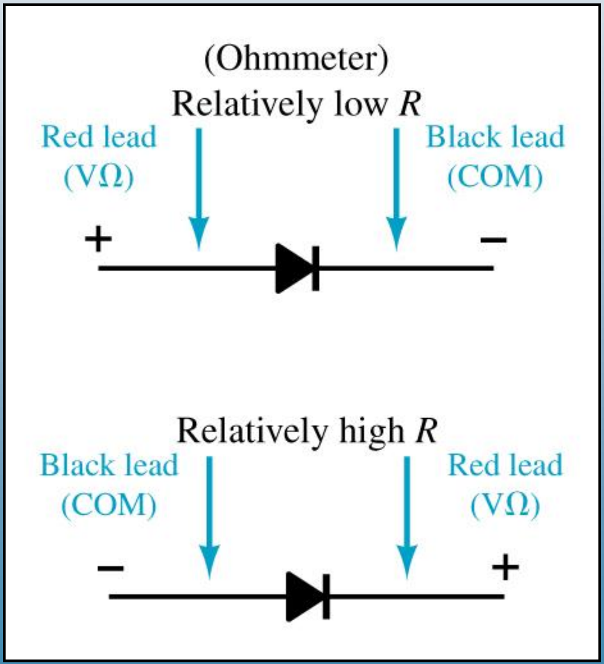
**Gallium arsenide ≅ 1.2 V**

**Silicon diode ≅ 0.7 V**

**Germanium diode ≅ 0.3 V**

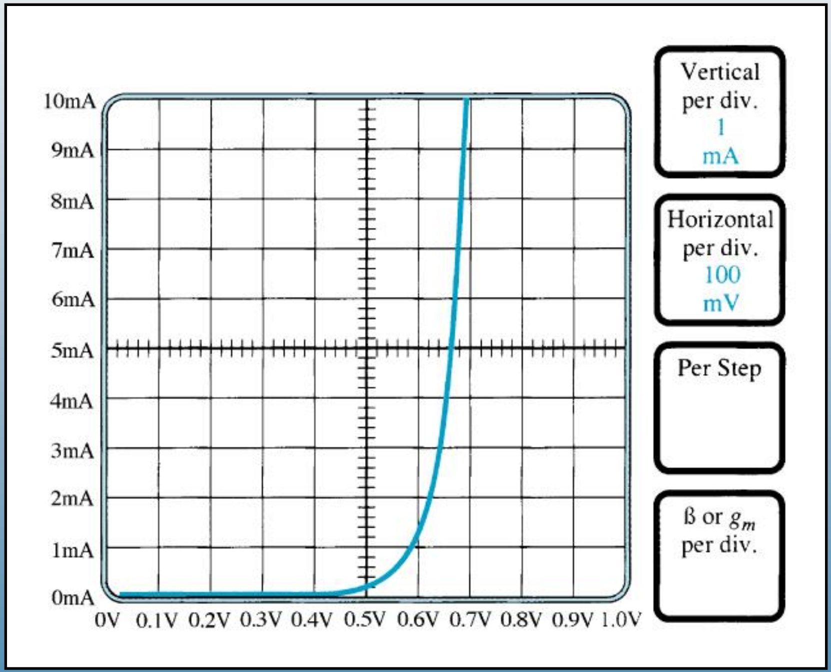
# Ohmmeter

An ohmmeter set on a low Ohms scale can be used to test a diode. The diode should be tested out of circuit.



# Curve Tracer

A curve tracer displays the characteristic curve of a diode in the test circuit. This curve can be compared to the specifications of the diode from a data sheet.



# Other Types of Diodes

There are several types of diodes besides the standard *p-n* junction diode. Three of the more common are:

**Zener diodes**

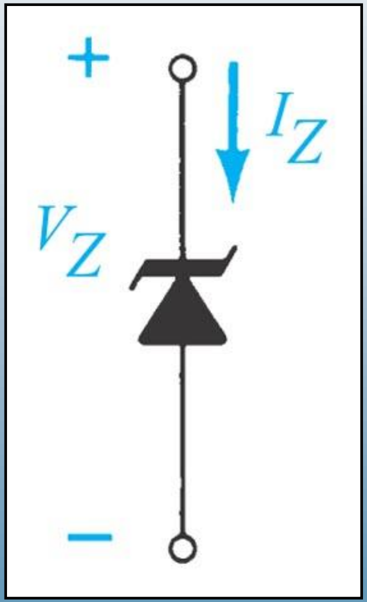
**Light-emitting diodes**

**Diode arrays**

# Zener Diode

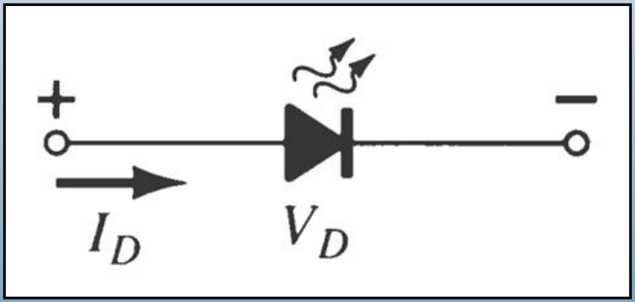
A **Zener diode** is one that is designed to safely operate in its zener region; i.e., biased at the Zener voltage ($V_Z$).

Common zener diode voltage ratings are between 1.8 V and 200 V



# Light-Emitting Diode (LED)

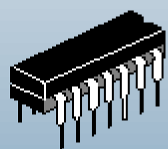
An **LED** emits light when it is forward biased, which can be in the infrared or visible spectrum.

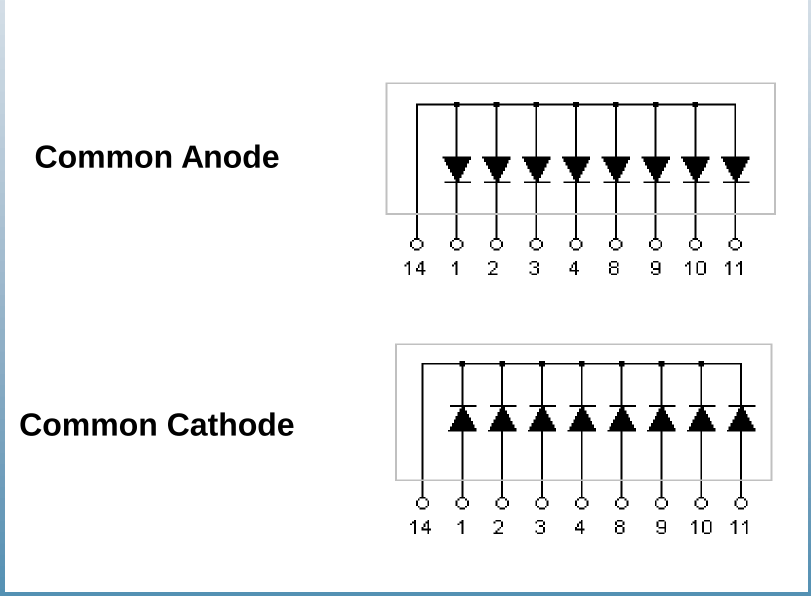



The forward bias voltage is usually in the range of 2 V to 3 V.

# Diode Arrays

Multiple diodes can be packaged together in an integrated circuit (IC).






**A variety of diode configurations are available.**